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SOME INFERENCES ON THE EQUATORIAL UNDERCURRENT IN THE INDIAN OCEAN BASED ON THE PHYSICAL PROPERTIES OF THE WATERS

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INTRODUCTION

THE International Indian Ocean Expedition, conducted during the period 1960-65, has provided a good amount of oceanographic data facilitating a study of the various features of the Equatorial Indian Ocean, which is least investigated of the three major Oceans, from the point of view of the current structure. One of the most fascinating problems of the study during the expedition concerns the subsurface currents. In view of the unique nature of the Indian Ocean due to its exposure to the monsoons, a study of the Equatorial Undercurrent in the Indian Ocean and its differences from the Equatorial Undercurrents in the other two major Oceans will be of special significance and interest. It is possible that a good knowledge of the subsurface currents of the Indian Ocean should help in gaining understanding of the true nature of the Undercurrent and in evaluating the various conflicting explanations of the Pacific and Atlantic Equatorial Undercurrents.

Studies on the Equatorial Undercurrent date back to 1886 when Buchanan first identified it in the Atlantic. It was rediscovered in 1952 by Cromwell, Montgomery and Stroup (1954) in the Pacific. Since then, it has attracted the attention of oceanographers, not only because it is new but also because the discovery seemed to provide an extremely interesting phenomenon in the equatorial regions of the oceans as this is concerned primarily with the physical processes controlling the fertility of the sea (Wooster, 1960, p. 263).

Recent measurements of the Undercurrent in all the three Oceans (Knauss, 1960, 1966 ; Montgomery and Stroup, 1962, Metcalf *et al.*, 1962, Knauss and Taft, 1964, Swallow, 1964) have shown that it is a fast and thin current having a maximum speed of 100-150 cm. sec.—1/(2-3 knots). It flows eastward beneath the surface and is reported to be symmetrical about the equator. The core of the current lies at a depth of 50 and 150 m.

An important thermal feature has been described by Wooster and Jennings (1955) who noted the association of the Undercurrent with physical features. The isothermal surfaces in the top layer of the thermocline ridge at the equator while in the deeper parts of the thermocline the isothermal surfaces trough. The thermocline contracts at a short distance north and south of the Equator, but close to the Equator there is vertical spreading of the thermocline and the weakening of thermal gradient. Distributions of other parameters also indicate features that appear to be closely related to the Undercurrent. Wooster and Cromwell (1958) noted that

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the oxygen content is mixed down from surface to depths not less than 300 m and near the surface the values are lower at the Equator than on either side of it. Similarly water of low phosphate appears to be mixed downward through the thermocline. Metcalf *et al.* (1962) first drew the attention to the significance of high-salinity core which evidently marks water carried east by the Undercurrent. The same was discussed in detail by Montgomery and Stroup (1962). Montgomery (1962, p. 488) suggested that the evidence of the Undercurrent can be found in the distribution of water properties such as (i) temperature or specific volume, (ii) oxygen or phosphate and (iii) salinity. Further indications of longitudinal and seasonal distribution of the Undercurrent could be gained from a systematic study of the thermal structure especially the equatorial troughing in the transequatorial sections (Montgomery, 1962).

MATERIAL AND METHOD

The sources of the material for the present investigation are the oceanographic data supplied by the National Oceanographic Data Centre, Washington, and the data published in the cruise reports of *R. V. Anton Bruun*, collected during the International Indian Ocean Expedition.

An attempt has been made to understand the seasonal and longitudinal variations of the Equatorial Undercurrent in the Indian Ocean from the characteristic features of the transequatorial distribution of the variables: temperature, salinity and dissolved oxygen content of the waters. In this connection twelve sets of meridional sections showing the distribution of temperature, salinity and dissolved oxygen were prepared from 5°N to 5°S along the various longitudes between 53°E and 94°E and they are shown in figures 1 to 12 for different months of the year. To facilitate an easy comparison of the distribution of these properties, each set of diagrams is superimposed and represented with different types of notation. The isotherms are drawn at an interval of 2.0°C while the equiscalar lines of salinity and oxygen are at intervals of 0.2‰ and 0.5 ml/L respectively.

RESULTS

Distribution of temperature: The surface waters in the Equatorial Indian Ocean do not show much seasonal variation of temperature, the annual range of temperature being 2.5°C. During the period December to April as shown in figures 1 to 3 and 12, there is spreading of the thermocline around the Equator and it contracts on either side where the vertical temperature gradients are very sharp. In the months of June and July the discontinuity layer contracts at the Equator and the isotherms diverge from about 1° to 2° south and north latitudes (Figs. 6 & 7). A comparison of the figures 4 & 5, clearly reveals the transition in the temperature structure taking place earlier in the eastern region than in the west. In a similar way sections 10 & 11 taken in the month of November indicate the contrast in the thermal structure along 86°E and 94°E. In the months of August and September the depth of thermocline is almost uniform without much latitudinal variation. The vertical gradients of temperature all along are practically the same.

Distribution of salinity: Similar to the thermal structure the field of salinity is also fairly uniform with salinity values above 33.0‰ and the highest being 35.6‰. Even the lower values that occurred are confined only to the upper few metres thick-

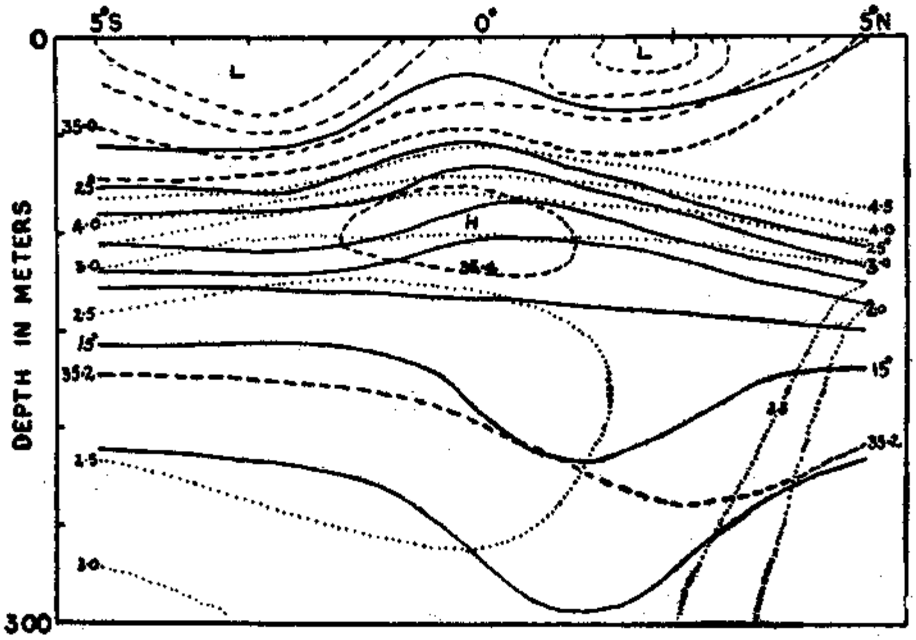

FIG 1. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 55°E (7-8 February 1964) from *Anton Bruun*, vertical exaggeration 2780.

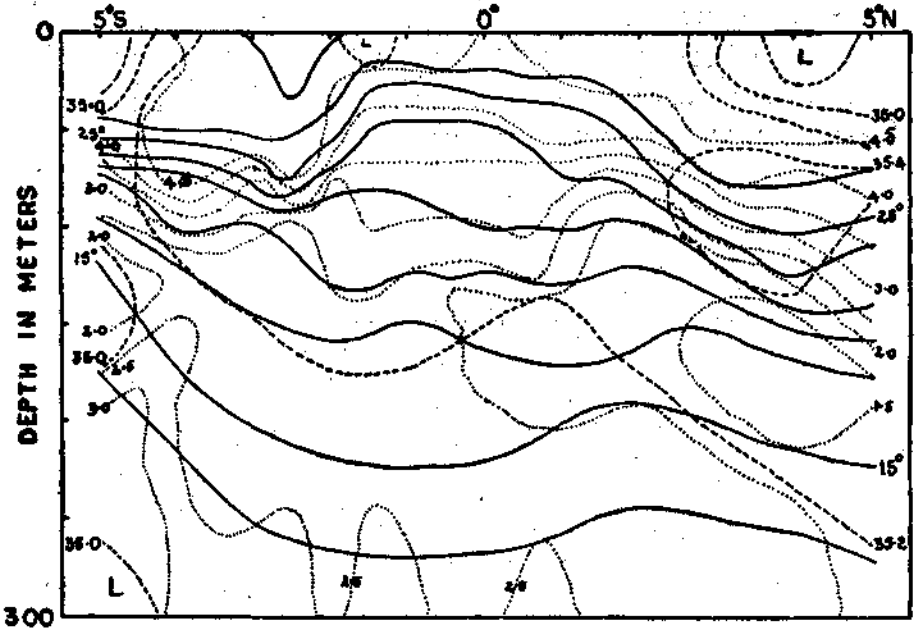

FIG. 2. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 61°E (5-12 March 1963) from *Argo*, vertical exaggeration 2780.

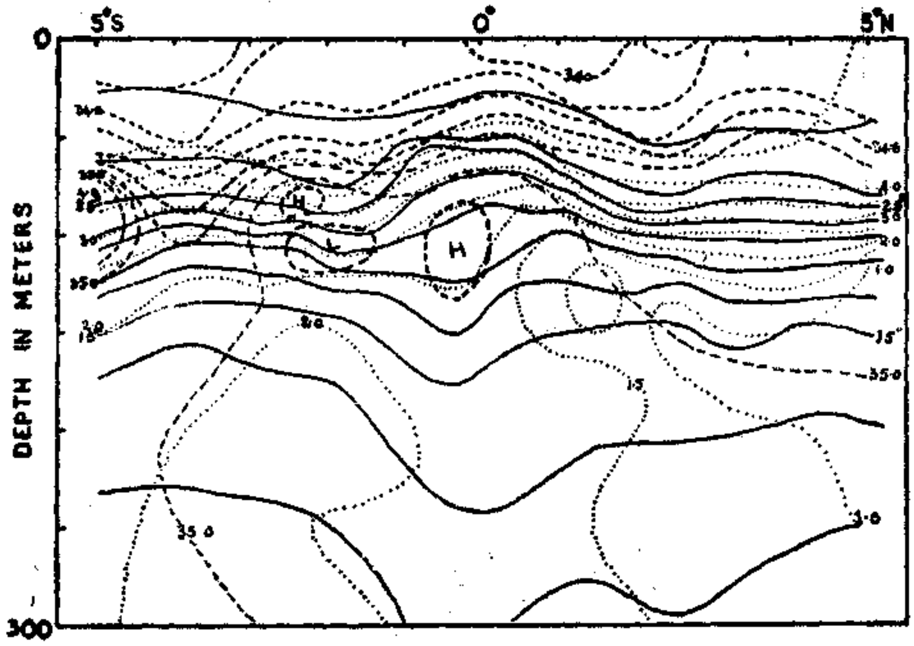

FIG. 3. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 92°E (19-25 April 1963) from *Argo*, vertical exaggeration 2780.

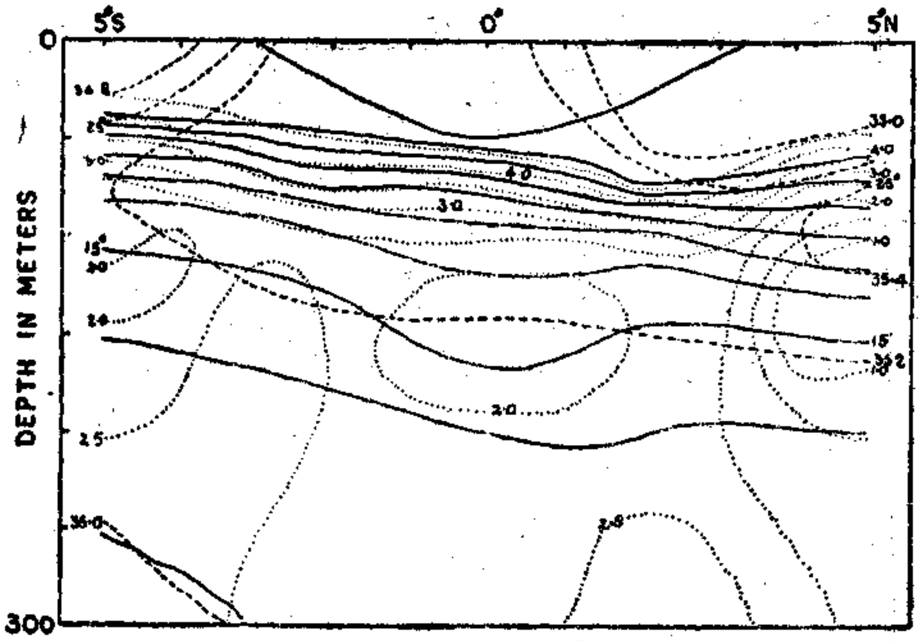

FIG. 4. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 65°E (24-31 May 1964) from *Anton Bruun*, vertical exaggeration 2780.

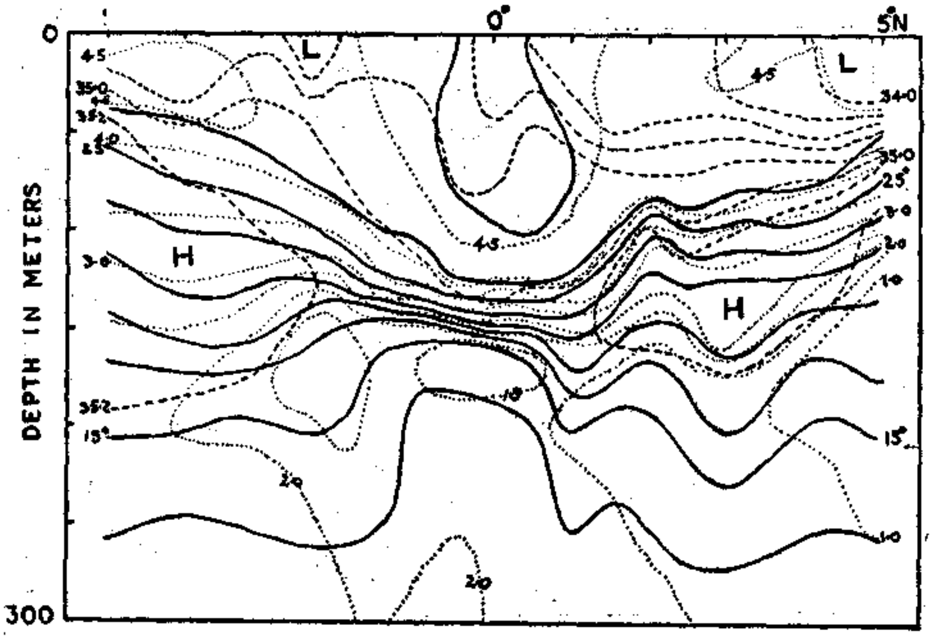

FIG. 5. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 84°E (26-31 May 1964) from *Pioneer*, vertical exaggeration 2780.

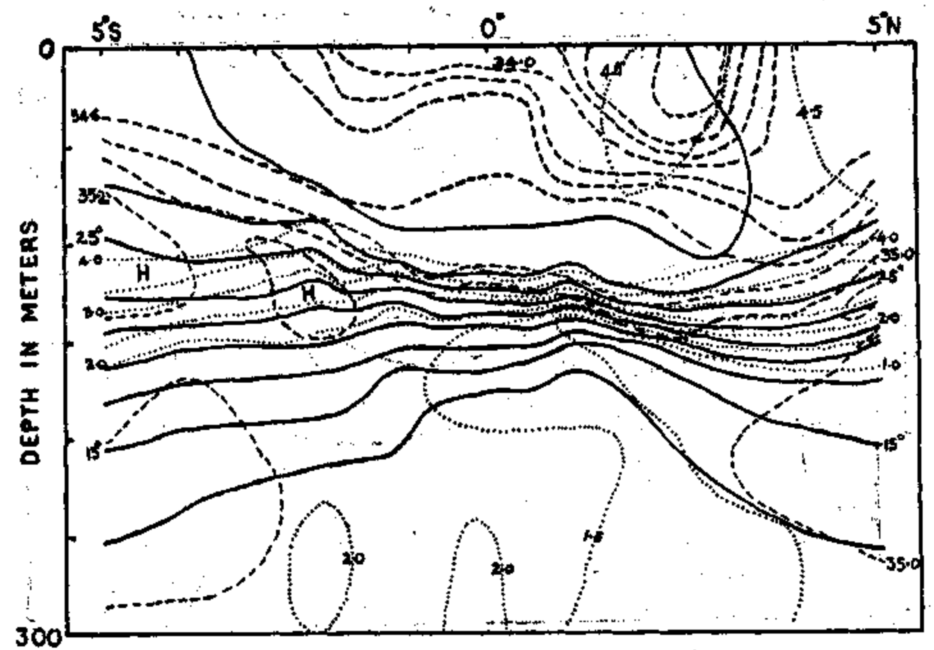

FIG. 6. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 92°E (13-18 June 1964) from *Pioneer*, vertical exaggeration 2780.

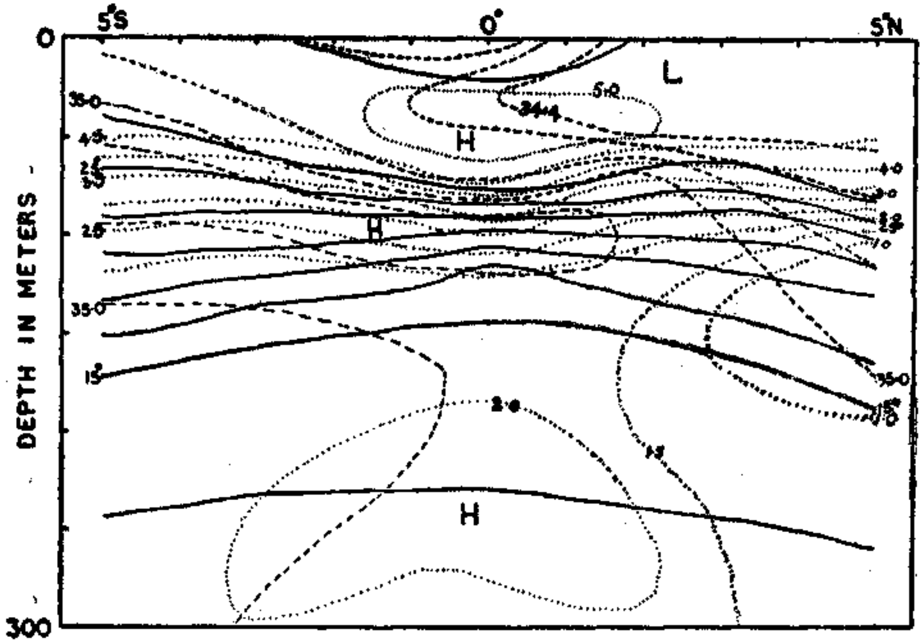

FIG. 7. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 80°E (14-17 July 1963) from *Anton Bruun*, vertical exaggeration 2780.

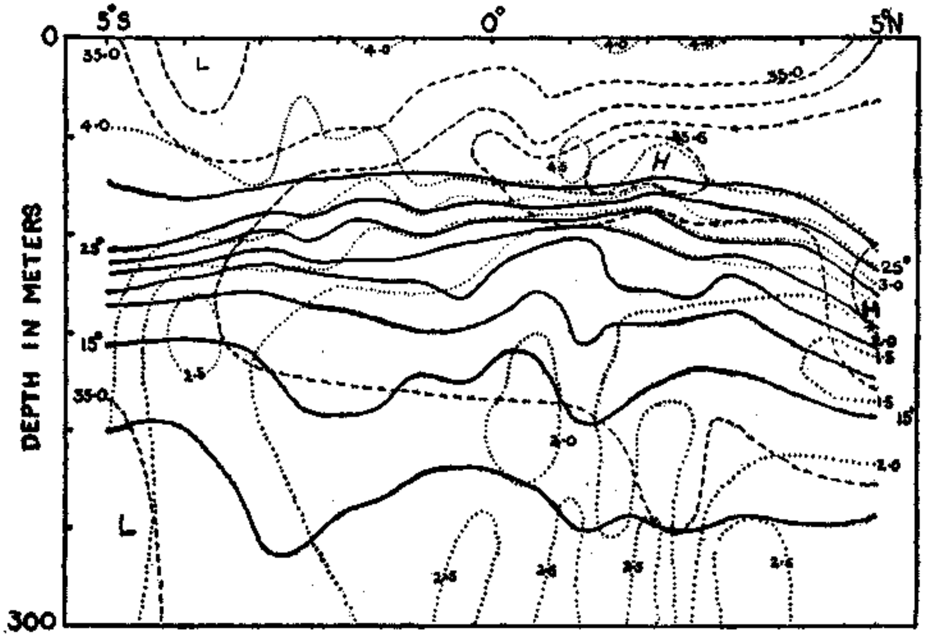

FIG. 8. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 62°E (14-21 August 1962) from *Argo*, vertical exaggeration 2780.

ness. A predominant feature of the salinity distribution is that north of the Equator a thin layer of low salinity prevails and increases to the south and west particularly from November to May. High-salinity water mostly either in the form of a core or tongue predominates in the layers of thermocline spreading as noticed in the figures 1 to 3 and 12. During the period May to November, though there is an increase in salinity from east to west it is not so pronounced. Generally, high salinity water exists either at the top of the thermocline or within it. A revival of salinity distribution takes place by the end of May just as in temperature distribution. In the sections where the contraction of thermocline takes place, in general, the tongues of high-salinity are separated by low-salinity water in the zone of contraction of the discontinuity layer. Mostly waters below 100 m depth are homosaline.

Distribution of dissolved oxygen : There is no significant variation either longitudinally or seasonally in the dissolved oxygen content of the equatorial waters. The most conspicuous feature in the oxygen distribution is that the isolines of the oxygen content follow the isotherms in the top 100 m thickness and the values are uniformly high. There is exceptionally very little deviation in this feature. Another prominent feature is that the oxygen content of the waters below the depth of 100 m increases from north to south, the lowest values occurring in these waters between 3°N and 5°N. Dissolved oxygen values less than 0.5 ml/L are virtually absent within the top layer of 300 metres in any of the sections. Mostly they are above 1.0 ml/L even in the deeper layers. In the zones of vertical spreading of thermocline, oxygen mixed waters penetrate deep in the region of spreading.

DISCUSSION

Thermal wind is defined by the equation: $\frac{\Delta u}{\Delta z} = -\frac{g}{fT} \cdot \frac{\Delta T}{\Delta y}$
where u is the eastward component of the current velocity, g acceleration due to gravity, f Coriolis force and T the mean temperature and y and z are positive northward and vertically upward respectively. This equation satisfies the phenomenon of Jet-stream, an analogous feature in the atmosphere as that of an Undercurrent in the oceans. Applying this equation to the oceans, it can be shown that where the isotherms slope down toward the Equator the eastward component of the geostrophic current increases upward, and conversely where the isotherms slope upward towards the Equator, the eastward component of the geostrophic current increases downward. It also follows that the strength of the current is proportional to the mean latitudinal gradient of temperature in the vertical. Hence the feature of troughing in the isothermal surface below the thermocline and ridging above the thermocline are the essential features for the Undercurrent to build up.

The equation of Thermal Wind given above also reveals that the strength of the eastward component of the current is more when the value of the Coriolis force f is small. This occurs very near the Equator which seems to be the contributing factor to the magnitude of the current in the oceans, whereas the latitudinal variation of temperature contributes mostly for the atmosphere, as the latitudinal variation of temperature in the oceans is much less compared to the atmosphere. Perhaps, this may be the reason why the Undercurrent, an analogous feature in the oceans as that of the Jet-stream in the atmosphere, is confined to the Equator.

Features such as the ridging of the isotherms above the thermocline and troughing below the thermocline are noticed from the month of November till the

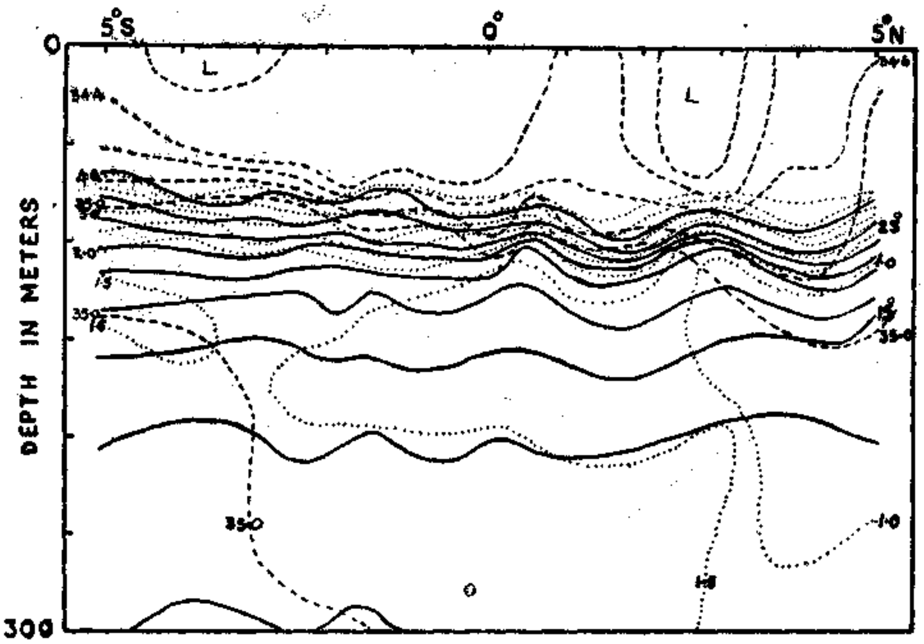

FIG. 9. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 89°E (12-21 September 1962) from *Argo*, vertical exaggeration 2780.

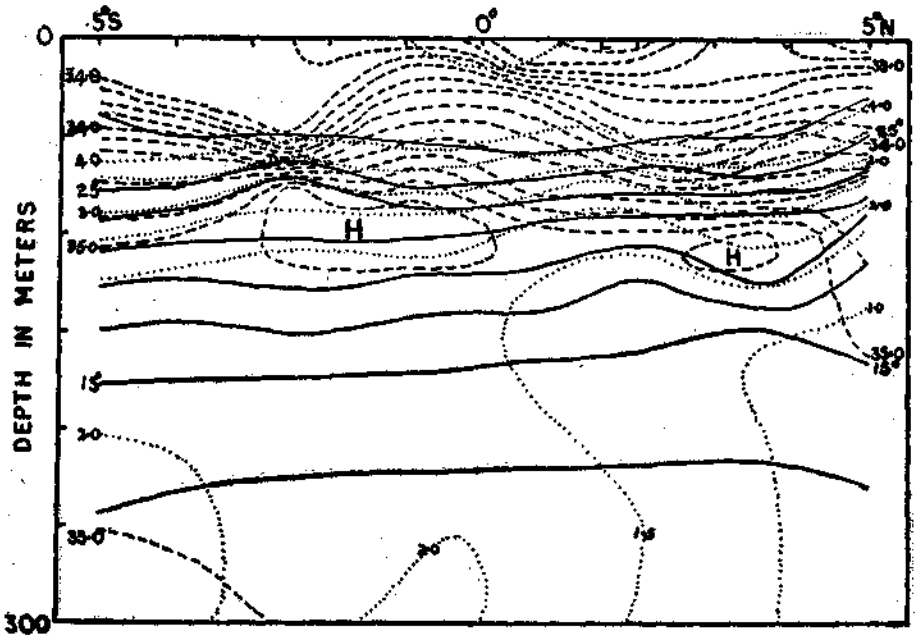

FIG. 10. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 94°E (25 November-1 December 1963) from *Koyo Maru*, vertical exaggeration 2780.

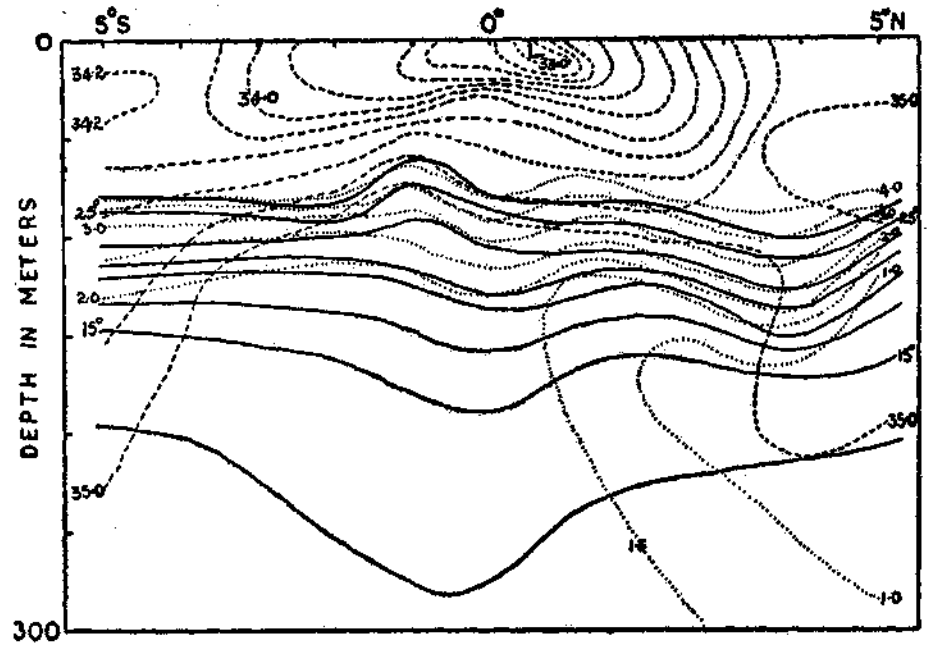

FIG. 11. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 86°E (26 November-4 December 1963) from *Kagoshi Maru*, vertical exaggeration 2780.

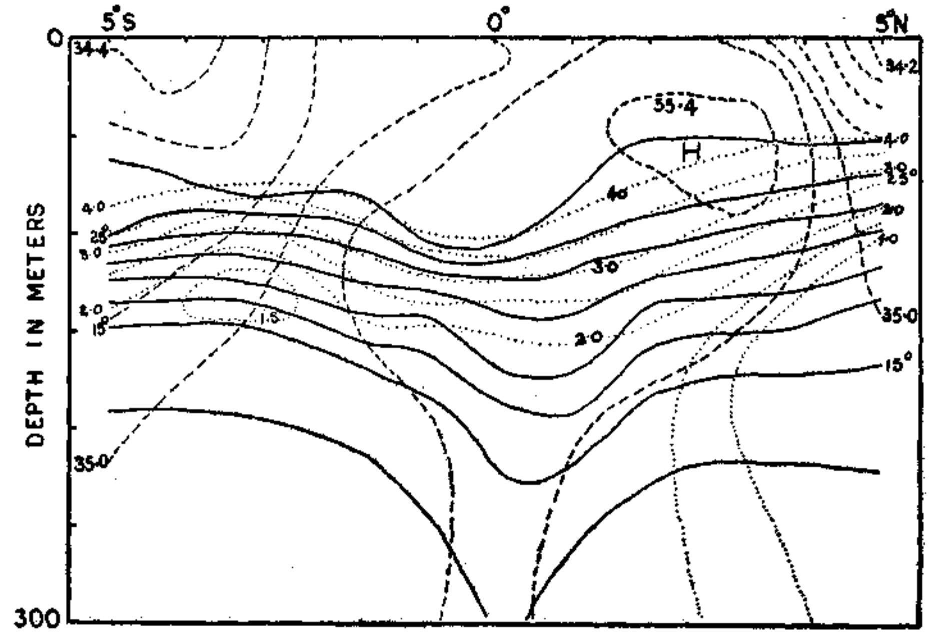

FIG. 12. Vertical section of temperature (solid lines, °C), salinity (dashed lines, parts per mille) and dissolved oxygen (dotted lines, ml/L) at 78°E (8-12 December 1963) from *Kagoshi Maru*, vertical exaggeration 2780.

end of May (Figs. 11 & 12 & 1 to 4) and they are more pronounced from February to April as depicted in the figures 1 to 3, indicating the presence of the Undercurrent in the Indian Ocean during that period. The existence of the Undercurrent is further concluded from the salinity and dissolved oxygen distributions where either a high-salinity core or tongue and mixing of the concentrated oxygen down to the deeper layers in the zone of thermocline spreading are noticed.

An examination of the figures 10 & 11 reveals the contrast in the appearance of an Undercurrent at 86°E and its non-existence at 94°E both sections being taken in the same year simultaneously. Similarly a comparison of the sections along 65°E and 84°E (Figs. 4 & 5) taken almost at the same time at the end of May, 1964, indicates the presence of the Undercurrent with the features of thermocline spreading, high-salinity core and mixing of concentrated oxygen down to the deeper layers in the former section while such indications are absolutely absent in the later section. Hence it is reasonable to infer that the formation of the Undercurrent takes place earlier in the west and continues to the east whereas the termination or break of Undercurrent occurs earlier in the east and extends gradually to the west. The former inference is further confirmed by the current measurements of Swallow (1964, Fig. 3) who noticed the existence of the current along 58°E even few days after the section taken along 65°E where there was no indication of the Undercurrent existing at that time. The strength of the current also seems to be more in the western region and it is very weak in the eastern zone as shown by the strength of the thermal gradients. Swallow's current measurements support the inference that the speed of the Undercurrent decreases towards the east (Swallow, 1964). But it goes against the observations of Knauss and Taft (1964) who inferred that the Undercurrent is absent in the west and its strength increases towards east. There is no earlier literature either to support or contradict the proposition that the Undercurrent develops earlier in the west. However, the nature of discrimination in the observations of the succeeding years may possibly be related to the inconsistency of the winds and consequently the surface currents particularly in the Eastern Indian Ocean during the transition periods : November and May (Verploegh, 1960, Charts 11, 12, 18 & 19).

The contraction of thermocline at the Equator and the vertical divergence of the isolines of oxygen content on either side of the Equator with the associated feature of low-salinity water at the Equator separating the tongues of high-salinity water in the months of June and July (Figs. 6 & 7) are the consequences of sinking at the Equator and upwelling on either side. The formation of the Undercurrent seems to be associated with the initiation of upwelling along the Equator in November and its break coincides with the beginning of sinking.

The commencement of the Undercurrent in the month of November and its disappearance in late May are in concurrence with the transition periods of mass redistribution as shown in the distributions of the thermal field and salinity (Figs. 4, 5, 10 & 11). Thus, the reversal of the slope of the sea surface does not proceed with the transition phase of the monsoons which occur, generally, in the months of April and October. Therefore, it seems appropriate to correlate the Undercurrent with the mass distribution rather than with the monsoons. Hence, the hypothesis that the easterly winds are responsible for the formation of the Undercurrent does not hold good at least for the Indian Ocean (Yoshida, 1959 ; Knauss, 1960). In April and May, though the easterly winds are absent, the Undercurrent persists probably because of the shear developed in the existing current systems during that period along the Equator *viz.*, the Equatorial Countercurrent and South-west Monsoon Current (Varadachari and Sharma, 1967, Figs. 4 & 5).

An examination of the location of the core of the Undercurrent as depicted by the oceanographic features, disclose that it is not confined to the Equator in the Indian Ocean, but, fluctuates about the Equator (Figs. 11 & 12 & 1 to 4). This is in accordance with Swallow's current measurements (1964, Fig. 3) in the Indian Ocean in the transequatorial section along 58°E where the core of the current was between 1°S and 2°S. Such assymmetry and fluctuations may be attributed to the oscillatory nature of the strength of the monsoon winds.

COMPARISON OF THE EQUATORIAL UNDERCURRENT IN THE INDIAN OCEAN WITH THAT OF THE PACIFIC AND ATLANTIC

In the Indian Ocean the Equatorial Undercurrent makes a seasonal appearance while in the other oceans it occurs throughout the year except on its termination very near the Islands (Knauss, 1966, p. 206, Rinkel *et al.*, 1966, p. 3898).

The high-salinity core within the thermocline is not as prominent as it is in the Atlantic (Metcalf *et al.*, 1962, Fig. 9 ; Reid, 1964, Fig. 3 ; Neumann and Williams, 1965, Figs. 4 & 6). As a matter of fact, even in the Pacific also it is not much pronounced (Knauss, 1960, Fig. 8c ; 1966, Figs. 9-11 ; Cromwell, 1954, Figs. 8, 24 & 30 ; Austin, 1954a, Fig. 8 ; 1954b, Figs. 12-15 ; Montgomery and Stroup, 1962, Fig. 4). As proposed by Knauss (1963) the variation may be the consequence of the difference in the salinity structure of the oceans.

The Undercurrent in the Indian Ocean shows assymmetry about the Equator and also fluctuations, whereas in the other two oceans it is strikingly symmetrical about the Equator (Knauss, 1960 & 1966, Metcalf *et al.*, 1962).

The author could come across the final report on the Equatorial Undercurrent of the Indian Ocean as observed by the Lusiad Expedition (Taft, B. A. and Knauss, J. A., 1967, *Bull. Scripps Instn. Oceanogr.*, **9** : 163 pp.) and also another preliminary report on the subject (Taft, B. A., 1967, *Proc. Intl. Confr. Tropical Oceanogr.*, Univ. Miami, 1965: 3-14) only after the paper was communicated for publication. In both these reports the Equatorial Undercurrent in the Indian Ocean is found to be present during late North-east Monsoon and it was inferred that probably the Undercurrent was not present earlier in January and February 1963. But, the present paper reveals that the Undercurrent exists from the end of November, particularly, in the western region. However, in general, the findings from these reports are in close agreement with those of the author.

SUMMARY AND CONCLUSIONS

1. Twelve sets of transequatorial sections in the Indian Ocean showing the distribution of temperature, salinity and dissolved oxygen content of the waters from 5°S to 5°N between 53°E and 94°E are presented for different months of the year and their features discussed.

2. November and the end of May are the transition periods for the mass redistribution in the Equatorial Indian Ocean.

3. The sections show clear evidences for the existence of the well known

Equatorial Undercurrent in the Indian Ocean from November to the end of May but, they do not support the thesis that the Undercurrent is confined to the Equator.

4. The development of the Undercurrent takes place earlier in the west and gradually extends to the east by November. Similarly, the break up or termination of the current extends from west to east by the end of May or the beginning of June.

5. The high-salinity core within the thermocline during the period of the appearance of the Undercurrent is not much pronounced as it is in the Atlantic.

6. The equation of Thermal Wind explains the features of the Equatorial Undercurrent.

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REFERENCES

AUSTIN, T. S. 1954a. Mid-Pacific Oceanography. Part III. Transequatorial waters, August-October 1951. *U.S. Fish., Wildl. Serv., Spec. Sci. Rept. Fish,* No. 131 : 50 pp.

———— 1954b. Mid-Pacific Oceanography. Part V. Transequatorial waters, May-June 1952, August 1952. *U.S. Fish Wildl. Serv., Spec. Sci. Rept. Fish,* No. 136 : 86 pp.

BUCHANAN, J. Y. 1886. On similarities in the physical geography of the great Oceans. *Proc. R. goegr. Soc.*, **8** : 753-770.

CROMWELL, T. 1954. Mid-Pacific Oceanography, Part II. Transequatorial waters, June-August 1950, January-March 1951. *U.S. Fish Wildl. Serv., Spec. Sci. Rept. Fish,* No. 131 : 179 pp.

————, MONTGOMERY, R. B. AND STROUP, E. D. 1954. Equatorial Undercurrent in Pacific Ocean revealed by new methods. *Science*, **119** (3097) : 648-649.

KNAUSS, J. A. 1960. Measurements of the Cromwell Current. *Deep Sea Res.*, **6**(4) : 265-286.

———— 1963. Equatorial Currents. *Trans. Amer. geophys. Union,* **44**(2) : 477-478.

———— 1966. Further measurements and observations on the Cromwell Current. *J. Mar. Res.*, **24**(2) : 205-240.

———— AND TAFT, B. A. 1964. Equatorial Undercurrent of the Indian Ocean. *Science*, **143** (3604) : 354-356.

METCALF, W. G., VOORHIS, A. D. AND STALCUP, M. C. 1962. The Atlantic Equatorial Undercurrent. *J. geophys. Res.*, **67**(6) : 2499-2508.

MONTGOMERY, R. B. 1962 ; Equatorial Undercurrent observations in review. *J. Oceanogr Soc. Japan, 20th Anniv. Vol.:* 487-498.

MONTGOMERY, R. B. AND STROUP, E. D. 1962. Equatorial waters and currents at 150°W in July-August 1952. *Johns Hopkins Oceanogr. Stud.*, I : 68 pp.

NEUMANN, G. AND WILLIAMS, R. E. 1965. Observations of the Equatorial Undercurrent in the Atlantic Ocean at 15°W during Equalant I. *J. geophys. Res.*, **70**(2) : 297-304.

REID, J. L., JR., (1964): A transequatorial Atlantic Oceanographic section in July 1963 compared with other Atlantic and Pacific sections. *Ibid.*, **69**(24) : 5205-5215.

RINKEL, M. O., SUND, P. AND NEUMANN, G. 1966. The location of the termination area of the Equatorial Undercurrent in Gulf of Guinea based on observations during Equalant III. *Ibid.*, **71**(16) : 3893-3901.

SWALLOW, J. C. 1964. Equatorial Undercurrent in the Western Indian Ocean. *Nature*, **204** (4957) : 436-437.

VARADACHARI, V. V. R. AND SHARMA, G. S. 1967. Circulation of the surface waters in the North Indian Ocean. *J. Indian geophys. Union*, **IV**(2) : 61-73.

VERPLOEGH, P. 1960. On the variation of climatic elements of the Indian Ocean. *K.N.M.I. publ.*, 102-77, Part II.

WOOSTER, W. S. 1960. Introduction-Investigations of the Equatorial Undercurrent. *Deep-Sea Res.*, **6**(4) : 263-264.

——— AND CROMWELL, T. 1958. An oceanographic description of the Eastern Tropical Pacific. *Bull. Scripps. Instn. Oceanogr., Univ. Calif.*, **7**(3) : 169-282.

——— AND JENNINGS, F. 1955. Exploratory Oceanographic observations in the Eastern Tropical Pacific, January to March 1953. *Calif. Fish. Game*, **41** : 79-90.

YOSHIDA, K. 1959. A theory of Cromwell Current (the Equatorial Undercurrent) and of the equatorial upwelling of an interpretation in a similarity to a coastal circulation. *J. Oceanogr. Soc., Japan*, **15**(4) : 159-170.